PART VII

THE POLAR FIELDS OF THE SUN AND THE MAGNETIC ACTIVITY CYCLE

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THE POLAR FIELDS AND TIME FLUCTUATIONS OF THE GENERAL MAGNETIC FIELD OF THE SUN

A. B. SEVERNY

Crimean Astrophysical Observatory, Nauchny, Crimea, U.S.S.R.

Abstract. In an attempt to summarize the present knowledge on the general magnetic field (gmf) of the Sun we pointed out the fine structure and the statistical nature of the gmf as one of its most important properties. The dipole-like behaviour of the mean polar field strengths is combined sometimes (since 1964) with a bias of the S-polarity flux for both poles. Highly uneven distribution of gmf with latitude and longitude, the disappearance of gmf at the South pole for months, and short period, almost synchronous at both poles, variations in the sign of gmf are pointed out. The fluctuations with time of the mean magnetic field of the Sun seen as a star (as well as mf at different latitudes) shows periodicity connected with the rotation of the Sun and very close agreement with the fluctuations of the interplanetary field (sector structure). The effect of faster rotation of N-polarities as compared with S-polarities as well as the bias of mean solar as well as interplanetary S-polarity fields are also pointed out. The possibility of short time-scale (hours) intrinsic changes in the local pattern of gmf is demonstrated.

1. Introduction

Starting from Hale's *et al.* pioneer work (1918), earlier observations (Langez, 1936; Adams, 1934, 1949; Babcock, 1948; Thiessen, 1946; Von Klüber, 1951; Beggs and

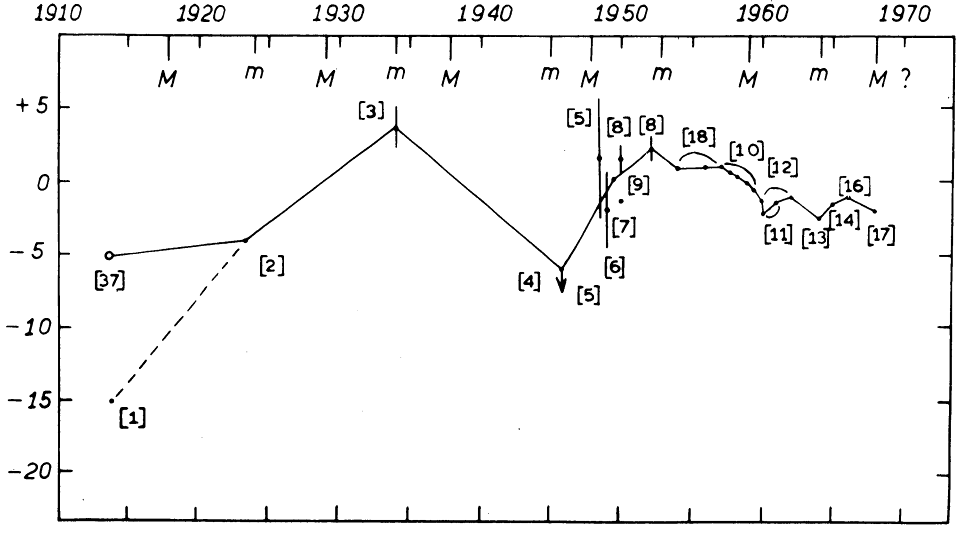

Fig. 1. Representing on a graph the separate determinations of the polarity and magnitude of the general magnetic field of the Sun. [1] = Hale *et al.*, 1918; [2] = Langez, 1936; [3] = Adams, 1934; [4] = Babcock, 1948; [5] = Thiessen, 1946, 1952; [6] = Adams, 1949; [7] = Von Klüber, 1951; [8] = Babcock and Cowling, 1953; [9] = Kiepenheuer, 1953; [10] = Babcock, 1959; [11] = Howard, 1965; [12] = Von Klüber, 1965; [13] = Severny, 1966; [14] = Severny, 1967; [16] = Stenflo, 1968; [17] = Stenflo, 1968; [18] = Babcock and Babcock, 1955; [37] = Stenflo, 1970*.

* As you will see from the following contribution of Dr. Stenflo the circle [37] on Figure 1, representing remeasured by him observations by Hale *et al.*, should be put somewhere near the zero line.

Howard (ed.), Solar Magnetic Fields, 675–695. *All Rights Reserved.*

Von Klüber, 1964; Babcock and Cowling, 1953; Kiepenheuer, 1953) of the general magnetic field of the Sun compiled on a graph (see Figure 1) permit one to suspect the existence of secular variations of the polarity and magnitude of the general field. (Here the ordinate is the difference: field strength at N-pole minus the same at S-pole). We observe that polarity reversals coincide more or less exactly with the epochs of maximum activity (M) while the minima of activity are approximately in phase with the strongest negative or positive fields, (except for the first determination by Hale (1918)). The graph includes also more recent observations in 1964–66 made in the Crimea (Severny, 1966, 1967; Stenflo, 1966a, 1968a) and 1968 simultaneous observations at Mt. Wilson and the Crimea (Stenflo, 1968a) showing the same negative polarity at N-heliographic pole and positive at S-pole, as it has had since 1959. The expected interchange of polarities between S and N poles during the maximum of activity has not appeared so far.

2. Statistical Properties of the General Magnetic Field of the Sun

Until 1952 the observations were based on measurements of Zeeman-shifted spectral lines in spectra of polar regions. These are of limited accuracy, and hence the errors were comparable with the magnitude to be determined. The photoelectric method introduced in 1952 (Babcock and Babcock, 1955) increased the sensitivity at least by 10 times, and the accuracy was determined only by the noise level. To increase the signal to noise Babcock and Babcock (1955) used a long slit and image-slicer collecting the light from an area $40'' \times 70''$. Although many important results were obtained, this brought a great deal of averaging and led to an overestimated role of the large scale magnetic fields, because the signal of the magnetograph, having an entrance area S and compensated for brightness fluctuations,

$$\delta i_{\parallel} \sim \sum_{i=1}^{n} \frac{S_i}{S} h_i \qquad (1)$$

is proportional to the area S_i and field strength h_i of a magnetic feature.

If the general magnetic field has fine structure (with dimensions $d_i < \sqrt{S}$), small elements ($S_i/S \ll 1$) do not contribute to the signal even if h_i is appreciable. As the signal:

$$\delta i_{\parallel} \quad \text{must be} \quad \geqslant \delta_i\,(\text{noise}) \qquad (2)$$

to be recorded, we can easily find (Severny, 1967) (using (1), the data about the noise level, and the weighted mean h, see below) that at a resolution of $23'' \times 23''$ (usual for Mt. Wilson) we lose information about all magnetic features with dimensions $\leqslant 8''$ ($\sim 40\%$ of total number, see histograms below) while at a resolution of $2''.5 \times 9''$ (Crimea) the corresponding loss is for sizes $\leqslant 3''$, ($\sim 10\%$ of total number).

If we increase the resolution, the amplitude (maximum field strength) of a given magnetic element (at a given scan) can increase by ~ 2.0–3.0 times, while the mean strength over an extended area (e.g. polar cap) also increases but only by ~ 30–50%

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(Stenflo, 1966b; Severny, 1967). This uneven increase is obviously due to (1) the fact that at low resolution the contributions into the sum (1) from opposite polarities are partly cancelled, and (2) the mean size (area) of magnetic features decreases with increase of resolution but slower than the field strength*. These effects are shown on Figure 2.

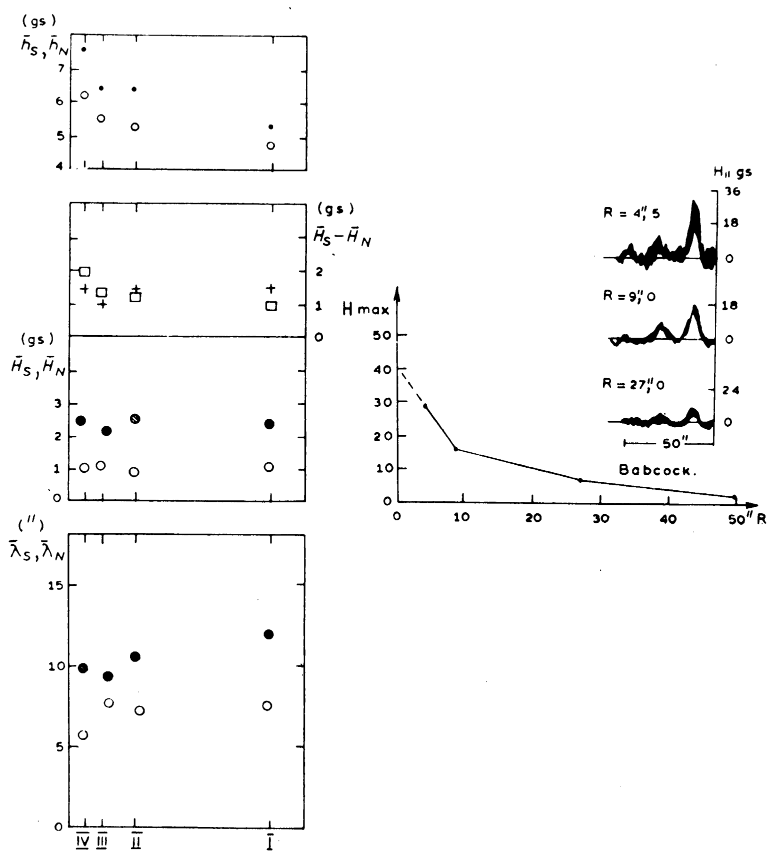

Fig. 2. Illustrating the influence of the resolution on the maximal field strength of a given element (right) and on the mean values of field strength h, mean flux H of S-(solid dots) and N-(open circles) polarity, and on the mean size of magnetic elements λ. The roman numbers correspond to different slit heights: I = 27″, II = 9″, III = 4″.5, IV = 2″.25 while the slit width remains the same = 2″.0.

We can see that the mean size at our highest resolution (2″.25) does not fall below 5″.

The problem arises: what are the smallest elements of the general magnetic field? The answer depends on the highest resolution, available at the present time only at Kitt Peak where it is 560 km (≃0″.65) at good seeing, and Livingston (1968) found that while brightness and velocity exhibit a spatial fine structure down to this highest resolution, *no similar* fine structure is found in the magnetic field. The smallest

* Of course, the net flux must remain the same at different R provided that we scan a given area without gaps and overlappings, cf. arguments between Stenflo (1966b) and Howard (1966).

elements seen on magnetic maps with $R = 930$ km square at Kitt Peak are 2″ while at our successive maps with $R = 2\overset{''}{.}3 \times 2\overset{''}{.}25$ the smallest cells persistent and reproducible on every map are $\simeq 2\overset{''}{.}5$ (see Figure 3). We think, therefore that *the smallest magnetic cells in quiet regions are about 2″ in size.*

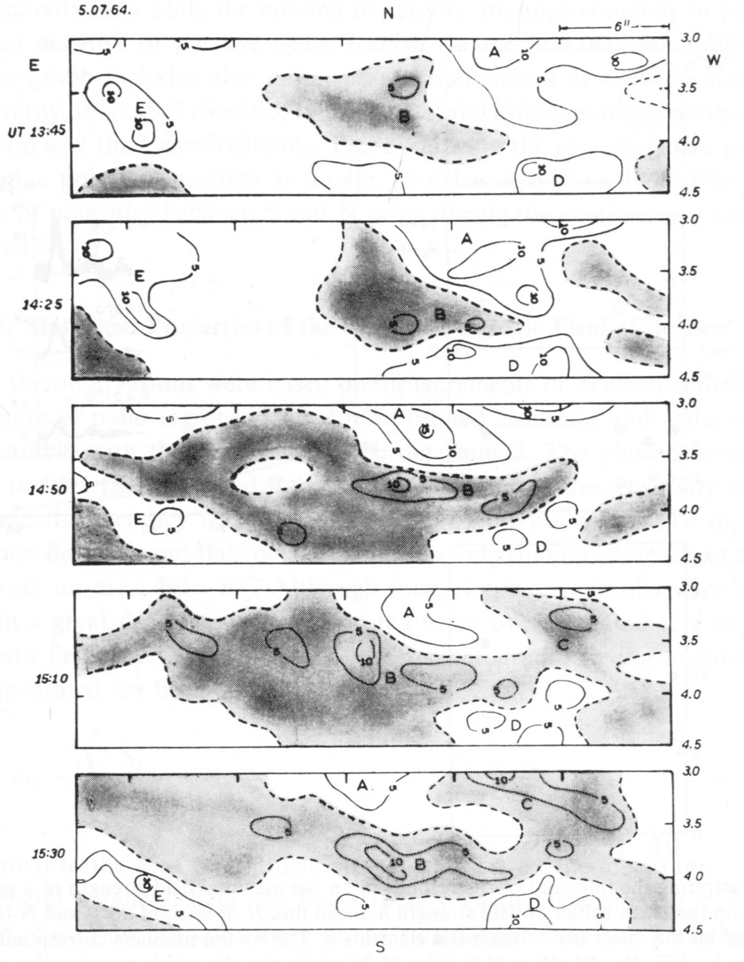

Fig. 3. High resolution (2″.5 × 2″.0) successive magnetic maps of a quiet region on the disk, showing the growth of opposite polarity in the previous region occupied by N-polarity.

All said above illustrates the fundamental role of resolution in examination of the nature of the general magnetic field.

The picture of the general magnetic field in quiet and polar regions looks like a carpet consisting of a large number of small elements, cells of different polarity, strength, and area mixed sometimes at random as Figure 4 shows. Extreme inhomogeneity and rapid time variations in this picture makes inadequate and accidental some

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old measurements of the general magnetic field at some separate fixed points (Adams, 1934, 1949; Babcock, 1948, 1959; Thiessen, 1946).

The effect of averaging at low resolution can also seriously distort the pattern obtained with the magnetograph (Babcock and Babcock, 1955) by producing so called 'UM-regions' – unipolar large-scale regions. These regions being unipolar at low resolutions appear as multipolar at higher resolution (see examples in Severny (1965)), and neither Crimean nor Kitt Peak magnetograms show such solid unipolar regions.

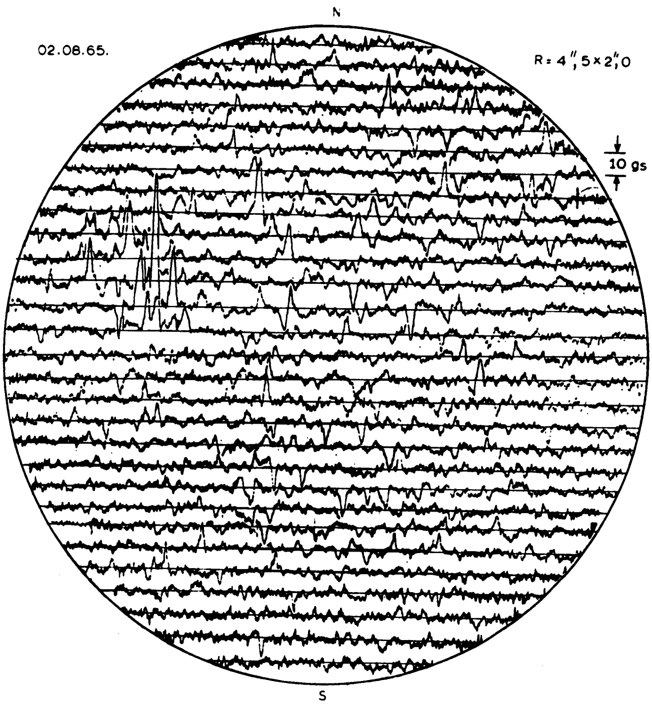

Fig. 4. The Crimean records of the magnetic field over the whole disk.

We think that the word 'unipolar' means only (the predominance) *the bias* in integrated flux of elements of a given polarity.

For quiet regions *at the center* of the disk we have the following values typical for the fine structure under consideration; while: $H_S = H_N = 3.74$ with peaks 20 G, (Crimea (Severny, 1967), $R = 2\overset{''}{.}5 \times 9''$, 1964–65), rms$(H) = \pm 4.9$ G, (Kitt Peak, $R = 10'' \times 10''$, (Livingston, 1966) and ± 2.8 G with peaks $\simeq 10$ G, ($R = 2'' \times 2''$ the same source).

The autocorrelation for magnetic features gives characteristic half-widths

$$r_m(0.5) = \begin{matrix} 8\overset{''}{.}5 & \text{(Crimea (Severny, 1967))} \\ 8\overset{''}{.}7 & \text{(Livingston (1966))} \end{matrix}$$

which is, by the way, *three times* as large as half-widths of the corresponding curve

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for velocities (Severny, 1965). Neither at Kitt Peak nor at Crimea has any correlation between magnetic fields and velocities been found: the coefficient of cross correlation never reached 0.2 for different latitudes. Meanwhile this coefficient is, as a rule, larger than 0.5 for simultaneous magnetic records at two different levels (corresponding to $\lambda 5250$ and $\lambda 6103$). These records also show an increase of autocorrelation radius and a decrease of the mean strength outside. Simultaneous records in $\lambda 5250$ and Hα show a decrease of mean field strength by 1.5 times from photosphere to chromosphere. The corresponding decrease found at Kitt Peak is $2.8/1.8 = 1.55$ (Livingston, 1966).

Before passing to polar regions we wish to emphasize that statistics for these regions differ but little from that just described for the quiet center of the disk. Histograms of

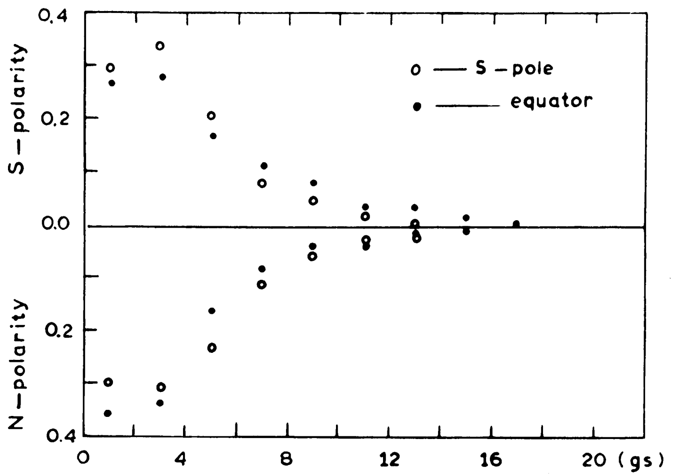

Fig. 5. Showing the similarity of histograms of field strengths at the polar and central regions of the disk.

field strengths on Figure 5 (Severny, 1966) are practically the same for polar and central regions, except for a slight increase of half width at the equator (see also Stenflo, 1968a). Livingston (1966) also writes that "magnetic structure shows no center-to-limb variation. Since at the center we see 'longitudinal fields' while at the limb 'transverse fields', we conclude the field distribution is isotropic". Histograms of sizes of magnetic cells in Figure 6 are also quite similar (the mean for the whole of 1965). As the weighted mean field at the center is a little stronger and not so concentrated (more fragmentary) as at the poles the distribution of field directions is rather semi-isotropic, with little bias of radial component as compared with transversal one. However this can also be due to the effect of projection near the border of the disk.

On the other hand, the histogram of sizes (Figure 6) as well as autocorrelation curves of magnetic elements do not show well defined characteristic dimensions ascribed to supergranulation (Leighton, 1965). Slight secondary maxima we have near 12″, 24″ and 48″ as if they were due to successive modes of standing surface waves on the Sun, (the same is also true for the 1964 distribution). If, according to Simon and Leighton (1964), strong fields correspond to the common boundaries of supergranules (fields higher than, say, 10 G) the weak fields belonging to the general magnetic field "are elements which have escaped the concentrating action of supergranular flow", (Livingston, 1968). The above mentioned absence of the correlation between magnetic and velocity structures is also suggestive in this respect because supergranulation is essentially a velocity structure.

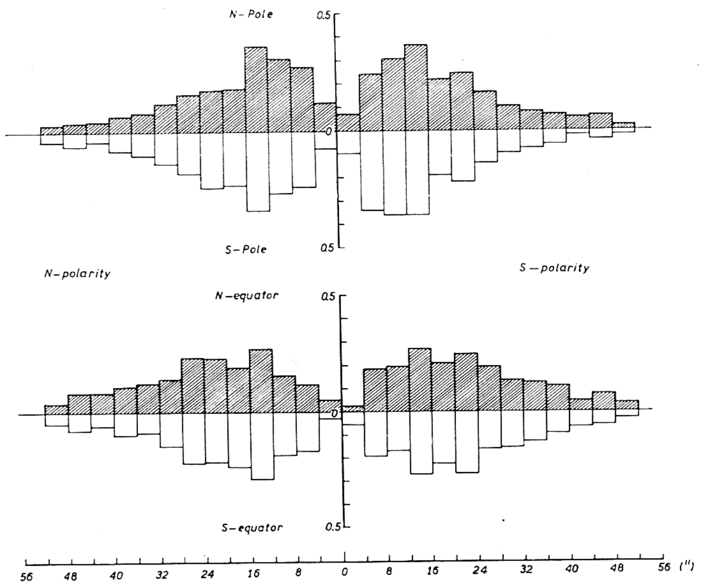

Fig. 6. The histograms of the sizes of 'magnetic elements' in polar and equatorial regions.

The mean statistical properties of polar field on the basis of more or less regular high-resolution records were followed in 1964 (27 days (Severny, 1966), 1965 (33 days (Severny, 1967)), 1966 (32 days (Stenflo, 1968)) and 1968 (Stenflo, 1968). At each day of observation the polar cap (or area 50°–75° in φ and $\pm 20°$ in λ) was scanned ($R = 4\overset{\prime\prime}{.}5 \times 2\overset{\prime\prime}{.}3$) and weighted over the number of elements. The mean strength

$$\bar{H} = \sum n_i H_i / \sum n_i$$

on the basis of the histogram was determined for each polarity and each heliographic pole separately. Also the mean flux was determined,

$$\bar{F} = \int H_{\|} \, \mathrm{d}l \,,$$

by planimetry of different scans in the area (also separately in the same way). The results are summarized in Table I, showing that the resulting field $H_N - H_S$ was invariably

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TABLE I

Resulting longitudinal field strength (weighted mean)

	1964 (I)	1964 (II)	1965	1966	1968
Pole N	−2.09	−1.09	−0.63	−1.02	−0.7
Pole S	+0.25	+0.98	+0.79	+1.11	+1.44

negative at the N-pole and positive at the S-pole and was of about the same value as if it were in the mean the field of a dipole, except for the first half of 1964, when the field practically disappeared at the S-pole. (It should be noted that the 1966 values of Stenflo (1968) were obtained by simultaneous records of a double magnetograph, and his results of 1968 (Stenflo, 1968) obtained at Mt. Wilson are not the weighted mean but the values of F averaged over a 27-day period of rotation.)

An essentially different pattern is displayed by the net flux F_N–F_S: it showed permanently through the years 64–65 and 68–69 (see below) a bias of S-flux or 'magnetic asymmetry', see Table II (for 64–65):

TABLE II

Ratio of magnetic fluxes F_S/F_N

	Ratio $F_S:F_N$	
Year	N-Pole	S-Pole
1964	2:0.5	1:1
1965	3.2:0.6	1.5:1

The effect was checked by direct planimetry of isogauss-maps and by comparison of the mean dimension of S- and N-polarity elements showing $\lambda_S/\lambda_N \cong 1.5$. This bias is exclusively due to the larger area occupied by the S-polarity. This magnetic asymmetry was reflected by the predominance of north polar flocculi according to Howard (1965) and accompanied by enhancement of all other activity (sunspots, K-plages, coronal, etc.) in the northern hemisphere. We will see that this 'monopole' – like behavior is also reflected by the interplanetary magnetic field.

The distribution of mean (averaged over $\pm 90°$ of longitude) field strength with latitude φ in polar regions shows the run which is rather opposite to that expected for a dipole, (Severny, 1967). Moreover if we pass now to the whole disk records, considering the same dependence on latitude we find no simple regularity: the mean field changes its sign very rapidly with latitude, several times between the N- and S-heliographic poles, see Figure 7 from Severny, 1967. The first change of polarity (moving from the poles) appears at latitudes 60–70°, and Stenflo at Mt. Wilson (1968) observed these first changes at $+70°$ and $-55°$, and correlated them to the zones of polar prominences. Some peaks in this latitude distribution of the general magnetic

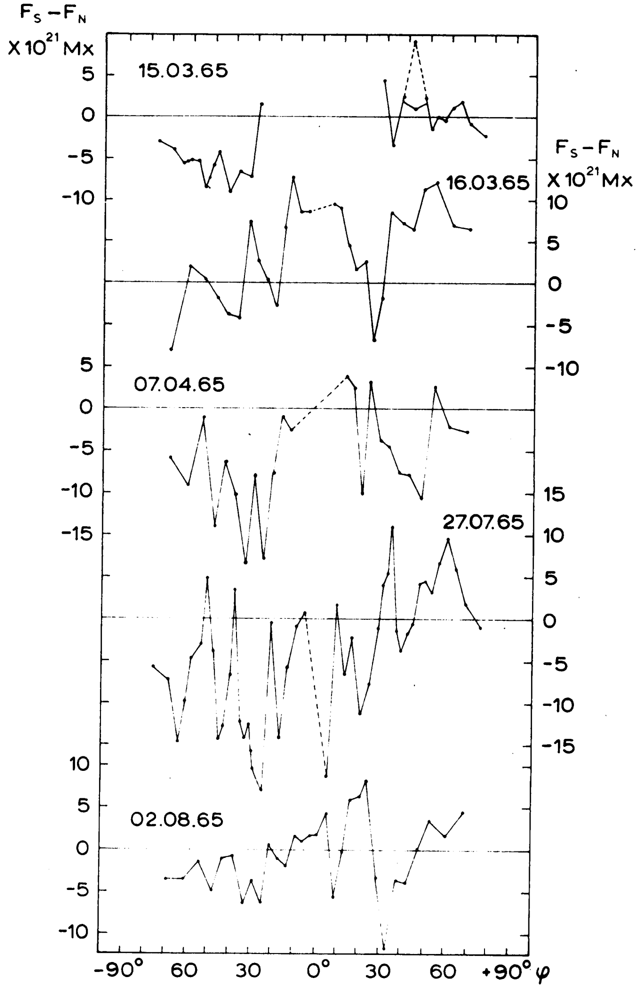

Fig. 7. The examples of the distributions with latitude of the mean (averaged over longitude) flux $F_S - F_N$ of the general magnetic field ($H_\parallel < 20$ G). (Vertical scales are units of 10^{+21} Mx.)

field can be identified from day to day, shifting gradually towards the equator (with a velocity 1–6 km/s). These results together with the differential rotation of the Sun point to the principal possibility when *one polarity overtakes the other polarity* thus giving rise to some kind of dynamo action (see below). It seems also impossible to bring such an asymmetrical (with respect to the equator) distribution of polarities into agreement with any dynamo-theory, even with one such as that of Steenbeck and Krause (1969), assuming quadrupole-like magnetic fields with S-magnetic pole at the equator.

This latitude-distribution also suggests that the high-latitude zones ($\varphi > 30$–40) can bring into the fluctuating net flux of the whole disk a *contribution comparable* with that for the low-latitude ($\varphi < 30$–40) zones (see e.g. the distribution for 7/04/65 where the flux $+7.88 \cdot 10^{21}$ Mx is mostly due to the high latitudes).

3. The Time Fluctuations of the General Magnetic Field

The most remarkable thing about the general magnetic field is, in our opinion, its *rapid fluctuations with time*. Babcock and Babcock (1955) were the first who observed that "irregular fluctuations in magnetic flux in the vicinity of the heliographic poles have been so large as to defy satisfactory explanations". They first noted the 'unprecedented' *disappearance* of the general magnetic field at the S-pole for 13 days (from July 29, 1954) and they claimed that they found annual variation of polar fluxes in

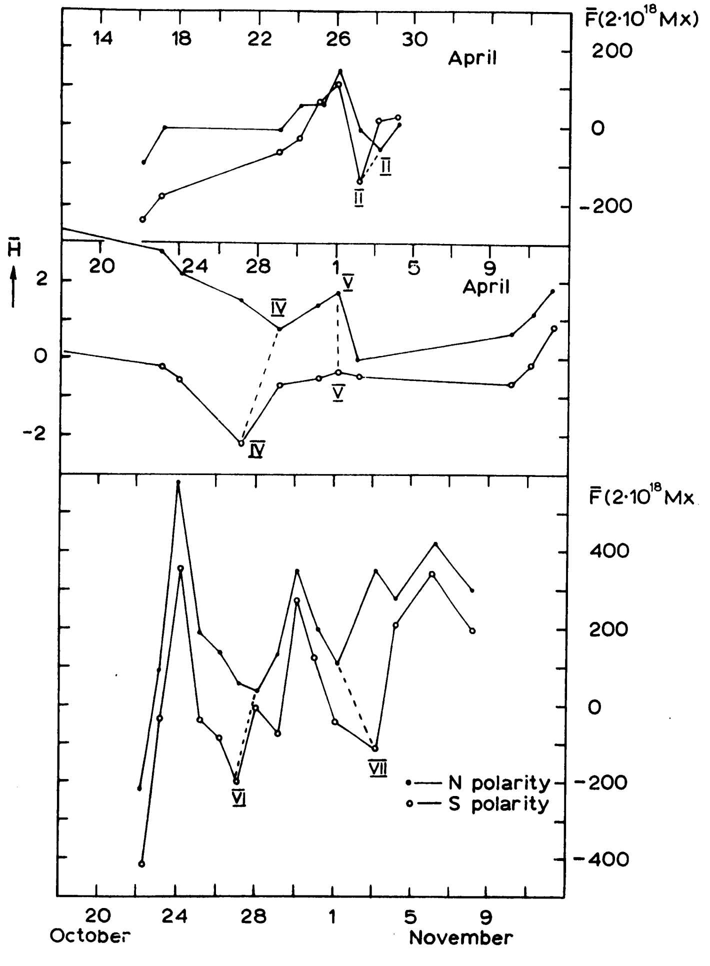

Fig. 8. Short time-scale fluctuations of the mean polar fields of the Sun recorded in August 1965 at Crimean Observatory (in the middle) and the same fluctuations according to data provided by Mt. Wilson Observatory (top and bottom) for April and October – November 1965.

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phase with the annual variation of the heliographic latitude of the Earth, B_0. The simultaneous appearance of the *same* positive (N)-*polarity at both helio-poles* for a period of more than one year (1957.5–1958.7) was first observed by Babcock (1959), who also demonstrated the lack of any correlation between long term variations of the general magnetic field at the poles and the heliographic latitude of the Earth.

The next disappearance of the general magnetic field at the S-pole was observed starting from March 1961 until the end of 1962 according to Howard (1965). He did not detect it in summer 1963 at Mt. Wilson and we could not detect it in the fall of 1963 as well as until September 1964 in the Crimea. Meanwhile at the N-pole we had quite measurable negative (S) polarity. Our more or less regular observations during 1965 showed several times (in March, July, September, October) the simultaneous appearance of negative (S) polarity general magnetic field at both poles. These 1965-

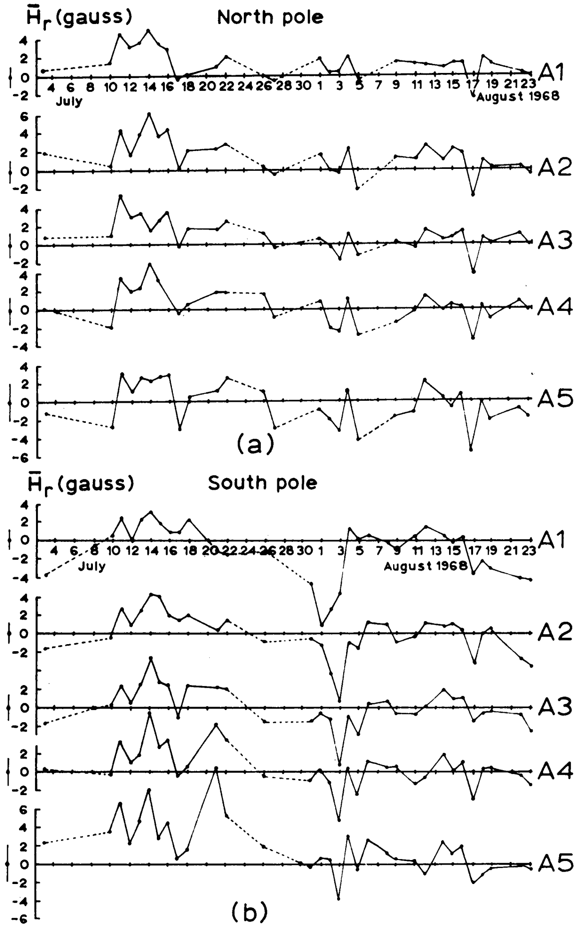

Fig. 9. Short time-scale fluctuations of the polar fields observed in 1968 at Mt. Wilson by Stenflo (1968b).

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fluctuations not only did not show any correlation with the sine-like run of B_0, but were rather of the opposite character.

Even more striking are *short time-scale fluctuations* (of the order of one day) illustrated in Figure 8 from Severny (1967). Remarkable here are the almost synchronous appearance of peaks at *both* poles, including the reversal of polarity. In 3 cases out of 4 the minima-peaks are about 1 day *earlier* at the S-pole than at the N-pole as if the positive (N) polarity tried to overtake the negative one. This looked very unlikely, but in 1968 Stenflo at Mt. Wilson (1968) observed the same strange simultaneous appearance of peaks at both poles (Figure 9), including also the reversals of polarity, (but no delay). In both cases Crimean and Mt. Wilson observations, the effect cannot be ascribed to the shift of the zero, because the corresponding records in non-magnetic lines do not reveal any such systematic error. Moreover Stenflo also found a highly uneven distribution of polar fields according to *longitudes* – very far from being rotationally symmetric and rather in a manner of sectors, (positive, negative then positive and negative again, see figure 10 from Stenflo (1968b). So that one can get a wrong estimate of the average polarity if the measurements do not cover one complete rotation at least.

The important question arises whether the time fluctuations specific for the polar fields are also specific for the whole solar disk or for the Sun as a star? Our high resolution (2.″3 × 9″) full disk records showed a variation of the net total flux in a

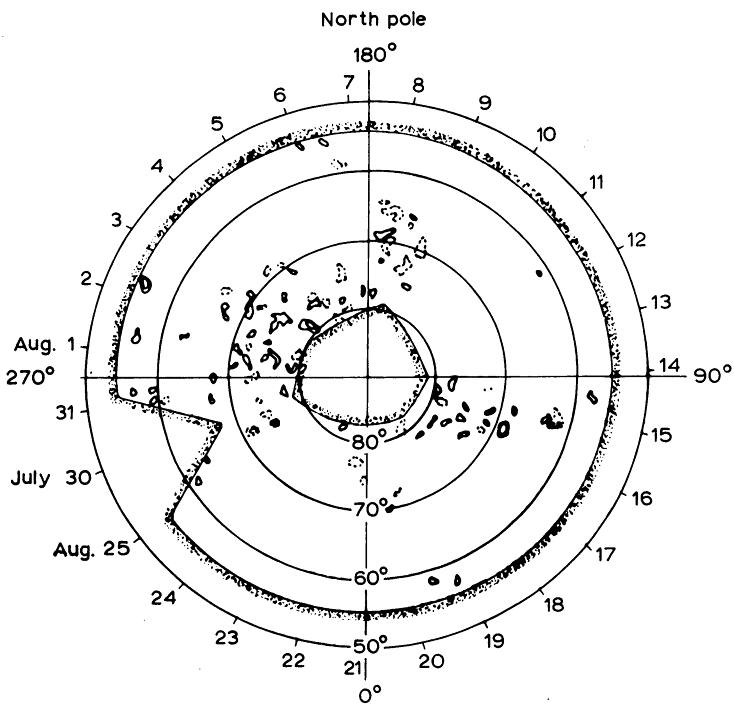

Fig. 10. The uneven distribution of polar fields according to longitudes according to Stenflo (1968b).

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matter even of a day (from -0.6 to $+0.5$ G for the magnitude of $F_{\text{net}}/4\pi R_{\odot}^2$), see Severny (1967). The disadvantage of such a record is that it takes almost a whole clear day – the time interval during which intrinsic changes of the general magnetic field can happen (see below). The low resolution ($23'' \times 23''$) full disk magnetic charts for seven rotations (starting in April 1961), being planimetered, showed much slower variations of net flux which remained always positive and repeating, with some time lag, the curve of daily sunspot numbers, (Bumba *et al.*, 1967). Disadvantages of such records are (1) the loss, as we said above, of information about the field of $\sim 50\%$ of the magnetic features, (2) the main contribution in the flux here was, according to the authors, from fields with a strength of 16 G (after proper calibration) which corresponds to Ca-plages and (3) all the fields around the border ($>60°$) were disregarded although, as we showed above, they can contribute a flux comparable with the central part of the disk.

Being incapable of increasing considerably the brightness of the solar image in order to reduce the time needed for high resolution scanning of the whole disk, we started, in the beginning of 1967, the more or less regular measurements of the magnetic field in the line 5250 of the whole solar disk using, instead of the solar image, a *parallel beam* from the coelostat mounting falling on the magnetograph slit of the Crimean tower telescope Severny (1969). This method provides immediately the mean (averaged over all elements of the image with the distribution of the brightness over the image as a weighting function) longitudinal field strength of the Sun seen as a star. As this strength is small – fractions of a gauss and the maximum amplitude of the noise can reach 3 G, we accumulate the weak signal during 15^m–20^m, leading to an accuracy of ± 0.15 G, (after subsequent planimetry of the records, all procedure is ~ 100 times shorter than full disk scanning measures). The most important point is to fix the position of the zero for the field strength which is made by similar records in the non-magnetic line ($\lambda 5123$) and the magnetic field strength is the difference between the mean reading for $\lambda 5250$ and that for $\lambda 5123$. (If we use the instrumental zero (dark current) instead of the mean signal from the non-magnetic line we can get an error of 300% and even the wrong polarity). Figure 11 plots these values for March–June 1968. As sunspots can in principle contribute to this field the total flux from all spots H_S (divided by the visible area of the solar disk) is plotted also according to routine observations of the solar patrol, (more precisely we plot the value $H_S = 0.15 \sum s_i H_i/\pi R^2$ where S_i is the area of the ith spot, including penumbra, having a maximum absolute value of field strength H_i inside the umbra; 0.15 is the mean ratio of umbral to penumbral area).

We see *a periodicity of fluctuations*: twice in the course of one rotation (27^d) we have positive and negative polarity, the mean time interval between + and − peaks is almost half of the rotation period. There can hardly be any doubt that these changes of the flux from the whole disk are due to rotation, and the peculiar behavior of the Sun is similar to a rotating quadrupole. The magnitude and the sign of the mean solar field can change very rapidly in a matter of one day and the change can be as large as 1 G per day. This is quite consistent with the above mentioned results (by Severny

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(1967) and Stenflo (1968)) about the rapid changes of the mean polar fields and it implies the idea that a wide range of latitudes is involved in these changes. An inspection of the Mt. Wilson synoptic magnetic charts by Wilcox and Howard (1968) shows that during several rotations we have more or less a clear demarcation in longitude between opposite polarities.

However the most remarkable point is the very close agreement between the mean solar field and the longitudinal component of the interplanetary field plotted in the same Figure 12, found by Wilcox *et al.* (1969), taking into account the transit time of solar wind plasma from Sun to Earth $=4\frac{1}{4}$ days. I will not enter into the details of this our common work with Dr. Wilcox on the comparison of the mean solar and interplanetary field which is in progress now. I wish only to make the following comments from the 'solar side' of the problem:

(1) From Figure 11 we see that the contribution of sunspots to the mean field can usually be disregarded. Moreover sunspot flux is either in antiphase with the mean solar field or disappears. Further if we plot (see Figure 12) also the latitude of the main sources contributing to the net flux which are usually preceding spots (leaders), and suppose that the behavior of the Sun as a magnetic star is determined only by sunspot magnetic fields, we find that the source determining the polarity of this magnetic star would pass *periodically* from N-hemisphere to S-hemisphere and back in the course of rotation. This periodicity follows also from the earlier work of Grotrian and Kunzel (1950). Meanwhile Wilcox and Howard (1968) and Shatten *et al.* (1969) demonstrated the existence of a correlation between the sign of the solar field and of the interplanetary field for a wide range of latitudes:* the peaks at ~ 5 day lags are

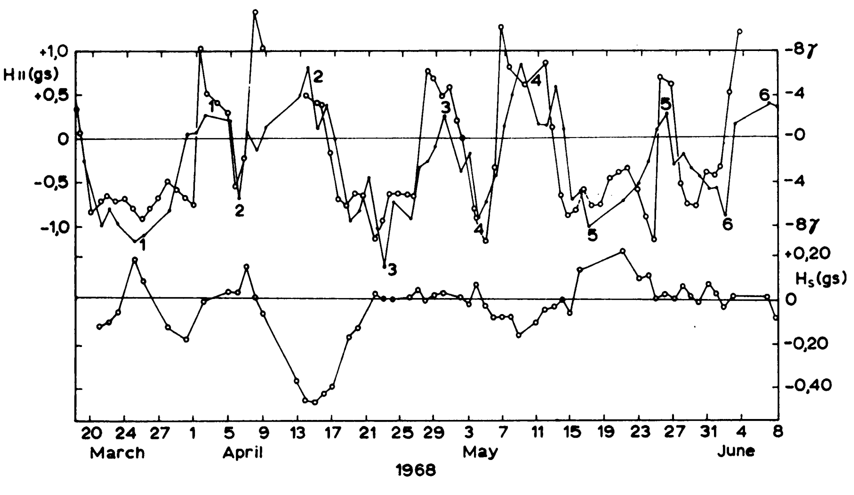

Fig. 11. The fluctuations of the mean magnetic field of the Sun seen as a star (solid dots, top) compared with the same fluctuations of the mean longitudinal component of interplanetary magnetic field (open circles, top). The fluctuations of the total flux of sunspots is plotted at the bottom.

* They used the synoptic chart method in which only the central (± 12 h) zone near the meridian is supposed to be responsible for producing the magnetism of interplanetary space.

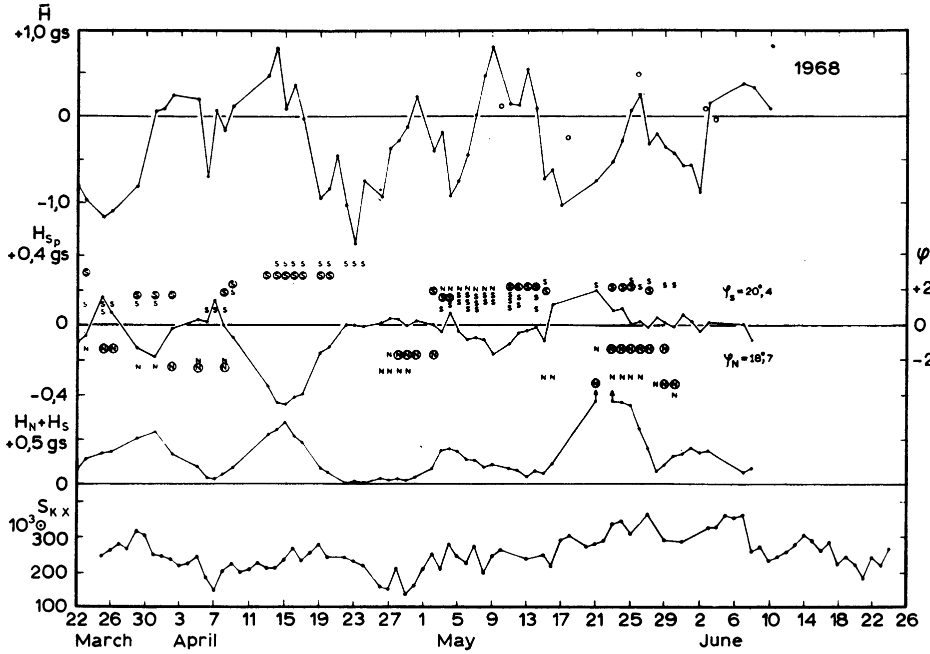

Fig. 12. The same as on Figure 11 fluctuations of the mean solar field (top) and of all sunspots H_{S_p} (solid line, second from the top) compared with the fluctuations in the position (latitude) of the principal contributor to the net sunspot flux (circles with the letter S or N), and with the area of Ca+ — plages (bottom).

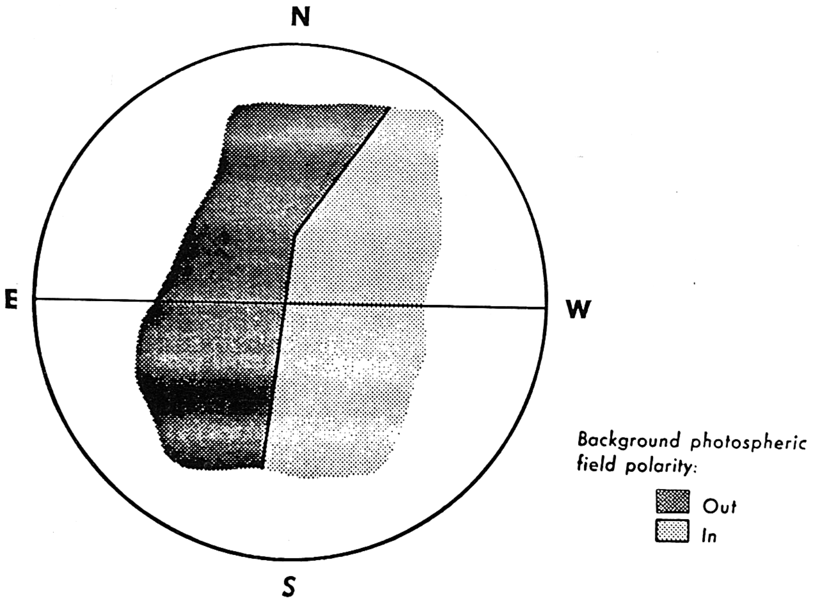

Fig. 13. The average solar sector boundary (1965) of the solar source of interplanetary magnetic field, see Wilcox *et al.*, 1969.

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clearly expressed for latitudes from $-40°$ to $+40°$, pointing again to the demarcation line close to the NS direction on the solar surface and to the longitudinal sector structure of the solar source of the mean field (Figure 13).

(2) The solar source of the interplanetary field could hardly be connected with active regions: good correspondence (within a factor less than 2) between the magnitudes of the solar and interplanetary fields shows that the solar wind is capable of dragging out the very photospheric fields with mean strength $\sim$1–2 G which can hardly be possible in active regions with strong fields where usually $V_A > V_S$, especially if we take Livingston's correction for the flattening of the line profile. This follows clearly from Shatzman (1962) and Mestel's (1968) considerations of the origin of the stellar wind. Now in the same Figure 12 we also plotted the total area of calcium plages S_p which characterizes the total magnetic flux of both polarities from active regions. There is no clearly defined correlation of this amount with the mean magnetic field we are measuring. Finally when we look carefully at cross correlations between polarities of solar and interplanetary fields (Schatten *et al.*, 1969) for different latitudes we can find that the height of the cross correlation peaks increases with increasing latitude and they are highest at $\varphi = \pm 40°$, i.e., when we are outside of the zone of solar activity, (Figure 14).

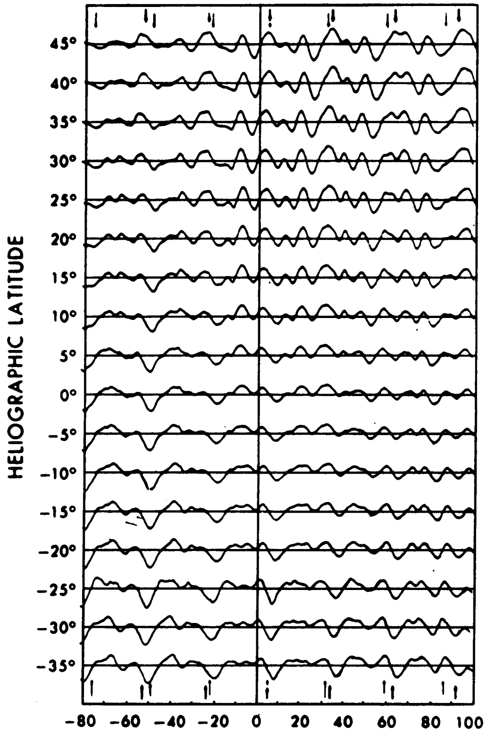

Fig. 14. The cross-correlations solar-interplanetary magnetic fields according to Schatten *et al.* (1969).

(3) If, further, we take the integral over time of the mean field fluctuations, we find the mean value to be -0.29 G, that is, the effect of magnetic asymmetry described earlier and existing since, probably, 1961. Now, the reality of this phenomenon is supported by the agreement between solar and interplanetary fields, and we can see for example in Figure 15 the same predominance in time of negative polarity in the interplanetary field during the whole of 1968. We think that well-known statement by Prof. Alfvén (1967) that magnetographic measurements are inadequate and lead to absurd results as regards the general magnetic field can now be laid to rest. The magnetic asymmetry is a real phenomenon and the nature of such a predominance of one polarity is one of the most challenging problems in solar physics.

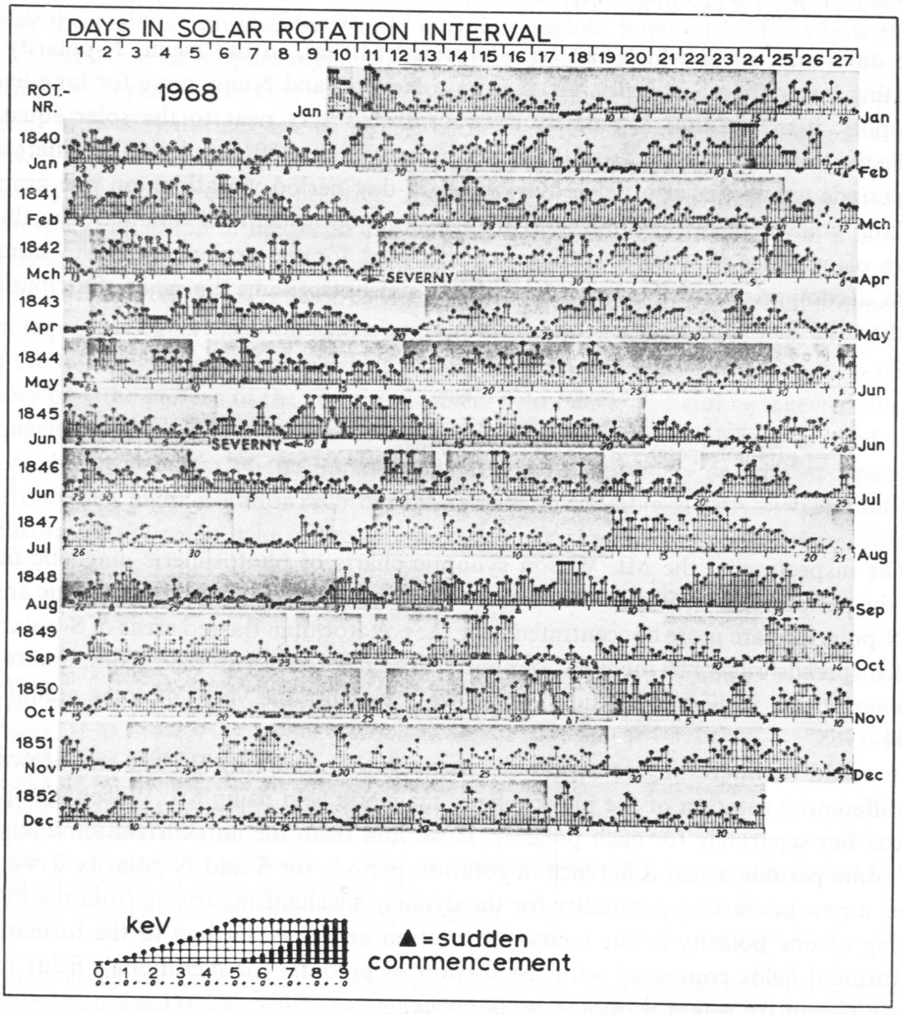

Fig. 15. Interplanetary magnetic sector structure (1968) overlayed on a chart of planetary 3-hr range indices *Kp*. It is seen the predominance of dark shading during 1968 pointing on the predominance on the field toward the Sun.

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(4) With the permission of Dr. Wilcox I wish also to make an additional remark: that 6-month's observations of mean solar field made in 1969 are also in agreement with the results just described, based on 1968 observations of solar and interplanetary fields.

(5) At first sight the periodic variations of the mean magnetic field of the Sun seen as a star, having two maxima and two minima during one rotation, show only accidental fluctuations of period (from 24 to 28.5 days). However if we compare (for 1968 and also 1969) the mean period between successive maxima (S-polarity) and minima (N-polarity) on the graph of $H_{\|}$ versus time we find

$$P_{\max}(S) = 27\overset{d}{.}60 \quad (10)$$
$$P_{\min}(N) = 26\overset{d}{.}8 \quad (9)$$

The difference is $0\overset{d}{.}8$ which can be interpreted as that, in the mean, N-polarity is rotating faster than S-polarity. Or, if we use Newton and Nunn curve for long-lived sunspots, it means that N-polarity is concentrated very near to the solar equator while the 'center of gravity', so to say, of S-polarity is near 20° lat. A similar difference of periods we obtain also if we overlap all 27-day period variations on one graph, making coincident all maxima, and then making coincident all minima. The third piece of evidence that such a difference can exist for the period 1968–1969 comes from a comparison of the mean latitude of sunspots giving the main contribution to the total flux from sunspots: we have

	1968	1969
φ(N-pol. spots) =	18.7 (24)	11.9 (94)
φ(S-pol. spots) =	20.4 (59)	16.1 (57)

The inspection of the Mt. Wilson synoptic charts of photospheric magnetic field for the period 1959–1966 also shows that sometimes (e.g. in 1959–1960) the blue areas of N-polarities are more concentrated near the equator than the red areas of S-polarity which spreads out up to the polar regions. This agrees also with the predominance of S-polarity flux in higher latitudes which we found for the years of solar minimum 1964–1965.

It would be interesting to repeat the investigation made by Wilcox and Howard of differential rotation of the photospheric magnetic field using Mt. Wilson synoptic charts but separately for each polarity. If we find from the autocorrelation analysis for some periods a real difference in rotation periods for S and N-polarity it would open a new interesting possibility for the dynamo mechanism, arising from the overtaking of one polarity in the course of rotation and thus, leading to the formation of toroidal fields connected with the torsion of poloidal (or meridional) fields in a way different from that proposed by Babcock.

(6) The fluctuations of the general magnetic field we have discussed so far were mostly interpreted as due to *rotation* of the Sun, having probably a stationary large

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scale four sector magnetic structure. The purpose of further investigations is to examine more closely this structure. However, besides these fluctuations and supposed 22-year-cycle of fluctuations of the general magnetic field with which we started our talk, there exist *intrinsic* short-time-scale fluctuations manifesting the hydromagnetic activity of the quiet solar surface (magnetic activity connected with active regions is, of course out of the scope of the present review). The large scale semiregular pattern of mean field is changing but slowly during several rotations showing attraction of features of the same polarity and repulsion of features of opposite polarity, as shown by Bumba and Howard* (1965). They found that sometimes weak features covering a large area apparently disappear over a period of few rotations. They found also, as did Meudon astronomers as well the continuing development of *new* magnetic regions *inside* the regions occupied by *the old* magnetic region. Some idea about how rapid this process can be in quiet regions is given in Figure 3. These charts, obtained in the Crimea by repeated frequent scanning of the same small area of the quiet Sun (resolution $2''.3 \times 4''.5$) during several hours, show clearly the process of emergence and growth of one polarity, B, inside the region primarily occupied mainly by the opposite polarity, A. The new-born polarity, B, pushes the 'old' one a little away, and the corresponding graph of magnetic flux shows that the original unbalance of fluxes for the area considered tends to disappear. All processes take about 2.5 hr. In other cases we have observed that a previously disappeared magnetic hill appears again and the whole process looks like a very slow oscillation on a time scale $\sim$2–3 hr. If the process we are talking about is characteristic for all quiet areas on the Sun and not an oscillatory one, the pattern of the general magnetic field on the disc can be renewed during a quarter of a day. These intrinsic changes of the general magnetic field coupled with those due to rotation of the Sun should present an extremely complicated pattern and only very high resolution records of the whole disk combined with 'zero-resolution' measures of the mean field of the Sun as a star can shed some light on the problem.

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* It remains unclear how large is the influence of the behavior of active regions on the conclusions drawn in Bumba and Howard (1965), because at the resolution of $23'' \times 23''$ used by these authors the signal from one element with size $2''$ and with the strength 10^3 G (Schröter-Beckers, or Sheely-elements) is equivalent to that from a uniform background field spread over the area $23'' \times 23''$ with strength 4 G minimal strength recorded on the charts in Stenflo (1970).

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Discussion

Altschuler: At this conference we have now heard at least three different groups state that they have seen rapid changes in the large scale photospheric magnetic field. You have seen rapid changes in the polar field, Wilcox has seen sudden changes in the sector boundaries, and we have evidence of rapid changes in the surface-harmonic spectrum of the photospheric magnetic field. The theoretical question that must now be posed I think is how such rapid changes in the large scale photospheric magnetic field can occur.

Cowling: You state that your observations cast doubt on the dynamo theory of solar fields. Babcock's theory began as a semi-empirical interpretation of observations. Theoreticians would be grateful if observers would agree what are the observations they ought to interpret. My second point is one which I think was made by Gold at Rottach-Egern. He pointed out that the structure of the solar plumes is remarkably constant, despite the rapid fluctuations in the photospheric field below. Are we to understand that plumes can rise indiscriminately from regions of north or south polarity, or that the tangles of opposite polarity do not extend more than a short distance above the photosphere?

Severny: I don't think we are now in a position to reject Babcock's theory which was, by the way, based on empirical grounds relating mainly to the strong sunspot field and was influenced to a larger extent by ideas of a dipole field, which is, if consistent at all, a very restricted meaning. If as we have shown, one polarity can overtake the other, the new possibility is offered: namely of the torsional dynamo effect because of differential rotation of different polarities. As to the second point the most plausible picture seems to me that proposed by Schatten *et al.* when the stable pattern of magnetic fields carried out with the solar wind should exist only outside of active regions where the Alfvén velocity is large compared with the sound velocity.

Nagarajan: The observations of the large scale field, its time structure and the sector structure explain why the classical dynamo theory is inapplicable. The hydro magnetic approximation has to be thrown away and one has to look at the possibility of having a nonstationary dynamo – presumably oscillating with complex multiple periodicities. One also has to treat the gas as in a non-equilibrium kinetic stage. Perhaps convection plays a larger role in the dynamo mechanism than just presenting a passing battery scheme, as, for example in the Biermann generator. Though these added complications make the models mathematically more complicated, they make it physically more reasonable.

Brueckner: Are the Mt. Wilson and Crimean observations of the simultaneous rapid changes of the 'general magnetic field of the Sun' in phase?

Severny: They probably can not be due to the difference in longitude, if we speak about short period fluctuations. For larger time-scales they agree quite satisfactorily, as Dr. Stenflo will probably speak about.

Pick: You have observed a good correlation between the mean photospheric field and the interplanetary magnetic field. In some cases, there seems to exist an anticorrelation between the interplanetary field and the main polarity of active centers. Is this true? And in this case, do you think that there may exist some reconnection between magnetic field lines originating from active centers and magnetic field lines originating away from the mean photospheric field? Thus this field reconnection would enable a sector to enlarge as it is seen during the increasing part of the cycle.

Severny: Yes it is true, and sometimes, as you have seen on my graph of mean solar field, we have just the opposite run on the overall flux from sunspots as the mean field in question. The kind of interaction between the mean photospheric field and the field of active centers should exist and I think that one of such suggestions of interaction as the one about which Prof. Tuominen will speak at this session.